NATIONAL RESEARCH COUNCIL PROJECT
(DSS File 07SQ 31926-3-0113)

DEVELOPMENT OF THE LAMB WET-CELL BURNER FOR ENERGY FROM NEW BRUNSWICK PEAT

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1985 April 15

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EXECUTIVE SUMMARY

The Lamb Gasifier was developed to combust unprepared wood and bark waste at 60% moisture content (wet basis) or less, and generate clean products of combustion at low excess air levels and maximal temperatures for a wide range of processes formerly fired with fossil fuels. Fuel is dried, pyrolized and gasified in the lower chamber and combustion of resultant gases is completed in the upper chamber. The process therefore combines combustion and gasification technology.

The physical and chemical characteristics of peat including ash and high moisture content strongly suggested the gasifier as an appropriate device for peat combustion. Interest has been expressed by Jiffy Products Ltd., Shippegan, New Brunswick, where gasifier heat output would be directed to a horticultural peat flash dryer and several ovens, replacing propane fuel.

As a first phase in the execution of such a project it was proposed that a pilot-scale equipment development and combustion test should be performed by Lamb using their 0.91m diameter test burner. This unit was built to develop design information for the original Lamb Wood Gasifiers and required refurbishment for use with peat.

A test burner facility was constructed in which air, fuel and flue gas streams were monitored into or out of the Gasifier in order to close mass and energy balances. Fuel was subjected to ultimate analysis and periodic checks of moisture and ash content. The flue gas was sampled and analysed using water cooled probes and particulate checks were performed.

An important aspect of equipment development was to confirm the viability of the undergrate feed system. This comprised a horizontal ram which pushed the fuel via a feed tube to a vertical screw on the vertical axis of the circular grate. The screw then conveys the fuel through the grate into the combustion chamber.

Shakedown trials indicated that the sealing effect of compressed fuel in the feed tube was adequate, though low pile and high output conditions occasionally produced back flow of smoke. Feed tube sealing is expected to improve on a full scale application.

Combustion tests indicated that the fuel pile did not have the permeability of hog fuel. In conjunction with the high specific area of the milled fuel, and low particle size, rapid release of volatiles followed small increases in underfire air rate. This led to disturbances in the pile, comparable to the onset of "bubbling" fluidization. Accordingly, combustion was controlled by overfire air rate.

Tests were performed using milled fuel peat of 46, 55 and 64% moisture content (wet basis). Thermal output was 2.75, 2.43, and 1.29 GJ/h respectively, and particulate emissions varied from 183 to 1370 mg/m3.

The test data and similarity criteria between the test unit and commercial units strongly suggest that a full-scale test be undertaken on a field unit. Some considerations of full-scale burner control and limitations to output are presented to restrict pile gas velocity.

RÉSUMÉ ADMINISTRATIF

Le réacteur de gazéification Lamb a été conçu pour brûler du bois non préparé et de l'écorce avec une teneur en humidité de 60 % (traitement humide) ou moins et pour produire des résidus de combustion propres à de faibles concentrations d'air en excès et à des températures maximales. Ce réacteur est destiné à remplacer des dispositifs alimentés avec des combustibles fossiles dans une large gamme de procédés industriels. Le combustible est séché, pyrolysé et gazéifié dans la chambre inférieure et les gaz résultants sont brûlés dans la chambre supérieure. Le procédé combine donc la technologie de la combustion et la technologie de la gazéification.

Étant donné les propriétés physiques et chimiques de la tourbe, qui contient des cendres et possède une haute teneur en humidité, le réacteur de gazéification semble tout indiqué pour la combustion de la tourbe. La société Jiffy Products Ltd., de Shippegan (Nouveau-Brunswick) s'est montré intéressée par cet appareil. La chaleur produite par le réacteur serait envoyée dans un séchoir-éclair de tourbe horticole et dans plusieurs fours, pour remplacer le propane.

Dans une première étape, la société Lamb a été chargée de mettre au point un dispositif pilote et d'effectuer un essai de combustion avec son brûler expérimental de 0,91 m de diamètre. Ce brûleur avait été construit dans le but de fournir des données nominales pour les premiers réacteurs de gazéification Lamb alimentés au bois et il a fallu le modifier pour pouvoir l'alimenter avec de la tourbe.

On a contruit un brûleur expérimental dans lequel les courants d'air, de combustible et de gaz de carneau à l'entrée et à la sortie du réacteur étaient monitorés de façon à équilibrer les bilans de matière et d'énergie. Le combustible était soumis à une dernière analyse et à des vérifications périodiques de l'humidité et de la teneur en cendres. Des échantillons de gaz de carneau étaient recueillis et analysés à l'aide de sondes refroidies à l'eau et des vérifications périodiques des émissions de particules ont été effectuées.

L'un des points importants dans la mise au point de l'équipement était de confirmer la validité du système d'alimentation à grille. Ce système comprenait un coulisseau horizontal qui poussait le combustible dans un tube d'alimentation vers une vis verticale sur l'axe vertical de la grille circulaire. La vis fait alors passer le combustible à travers la grille dans la chambre de combustion.

Des essais initiaux ont montré que l'effet de scellement du combustible comprimé dans le tube d'alimentation était adéquat, bien qu'on ait observé à l'occasion un refoulement de fumée lorsqu'il y avait peu de combustible et lorsque le rendement de la combustion était élevé. On prévoit que le scellement du tube d'alimentation sera meilleur lorsqu'on passera à l'échelle réelle.

Des essais de combustion ont montré que la pile de combustible n'a pas la perméabilité des résidus. En conjonction avec la grande surface spécifique du combustible broyé et la petite taille des particules, on a observé un dégagement rapide de produits volatils lorsqu'on augmentait légèrement la quantité d'air envoyé sous la grille. Cela a entraîné des perturbations dans la pile de combustible comparables à ce qu'on peut observer au début de la fluidisation à "bullage". En conséquence, on a augmenté le rendement de la combustion en envoyant l'air par le dessus.

Des essais ont été effectués avec de la tourbe broyée ayant une teneur en humidité de 46, 55 et 64 % (traitement humide). La production de chaleur était respectivement de 2,75, 2,43 et 1,29 GJ/h et les émissions de particules variaient de 183 à 1370 mg/m^3.

Les résultats des essais et des critères de similitude entre le dispositif expérimental et les dispositifs industriels indiquent qu'on devrait entreprendre des essais à l'échelle réelle avec un dispositif industriel. Le rapport inclut quelques remarques sur la commande du brûleur à l'échelle réelle et sur la limitation de la combustion dans le but de réduire la vélocité des gaz dans la pile de combustible.

1.0 INTRODUCTION

The Lamb Gasifier was developed to combust unprepared wood and bark waste at 60% moisture content (wet basis) or less and generate clean products of combustion at low excess air levels and maximal temperatures for a wide range of processes formerly fired with fossil fuels. Fuel is dried, pyrolized and gasified in the lower chamber and combustion of resultant gases is completed in the upper chamber. The process therefore combines combustion and gasification technology. The gasifier is pictured in Fig. 1 and shown schematically in Fig. 2.

The physical and chemical characteristics of peat including ash and high moisture content strongly suggested the gasifier as an appropriate device for peat combustion. Interest has been expressed by Jiffy Products Ltd., Shippegan, New Brunswick, where gasifier heat output would be directed to a horticultural peat flash dryer and several ovens, replacing propane fuel.

As a first phase in the execution of such a project it was proposed that a pilot-scale equipment development and combustion test should be performed by Lamb using their 0.91m diameter test burner (Fig. 3). This unit was built to develop design information for the original Lamb Wood Gasifiers and required refurbishment for use with peat.

Successful demonstration of peat combustion in the pilot gasifier/combustor would encourage a second phase of the project, installation of industrial-sized equipment as a demonstration project.

FIGURE 1 -- LAMB GASIFIER/COMBUSTOR

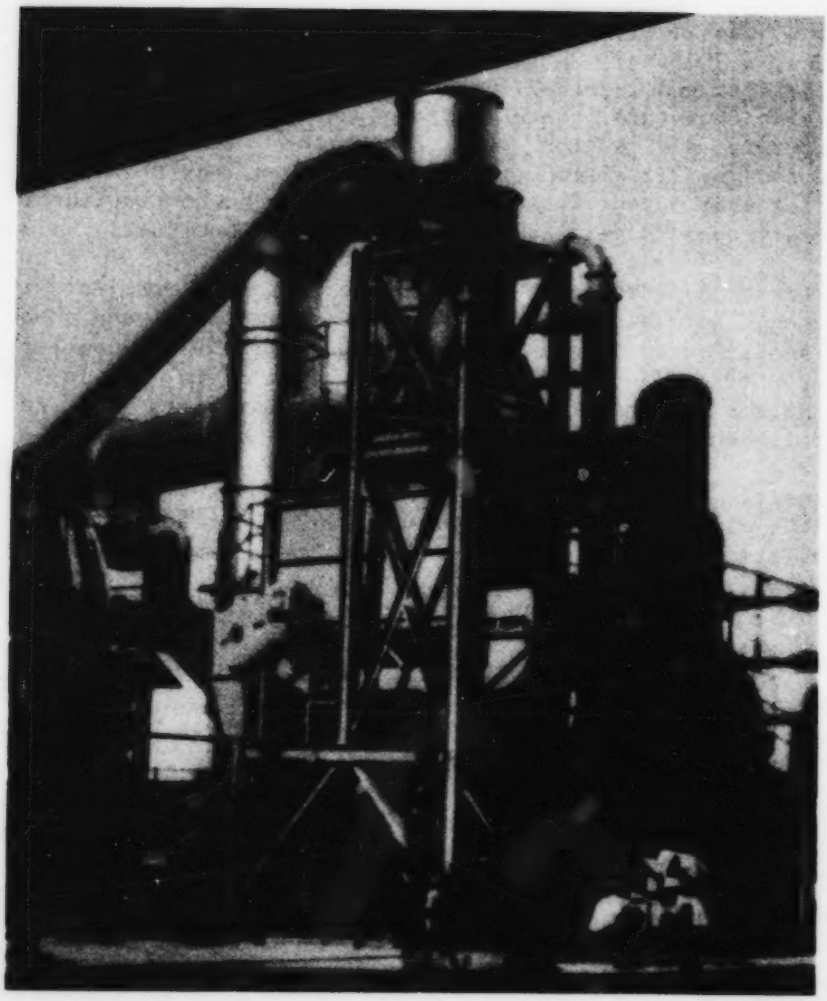


FIGURE 2 -- LAMB GASIFIER/COMBUSTOR SCHEMATIC

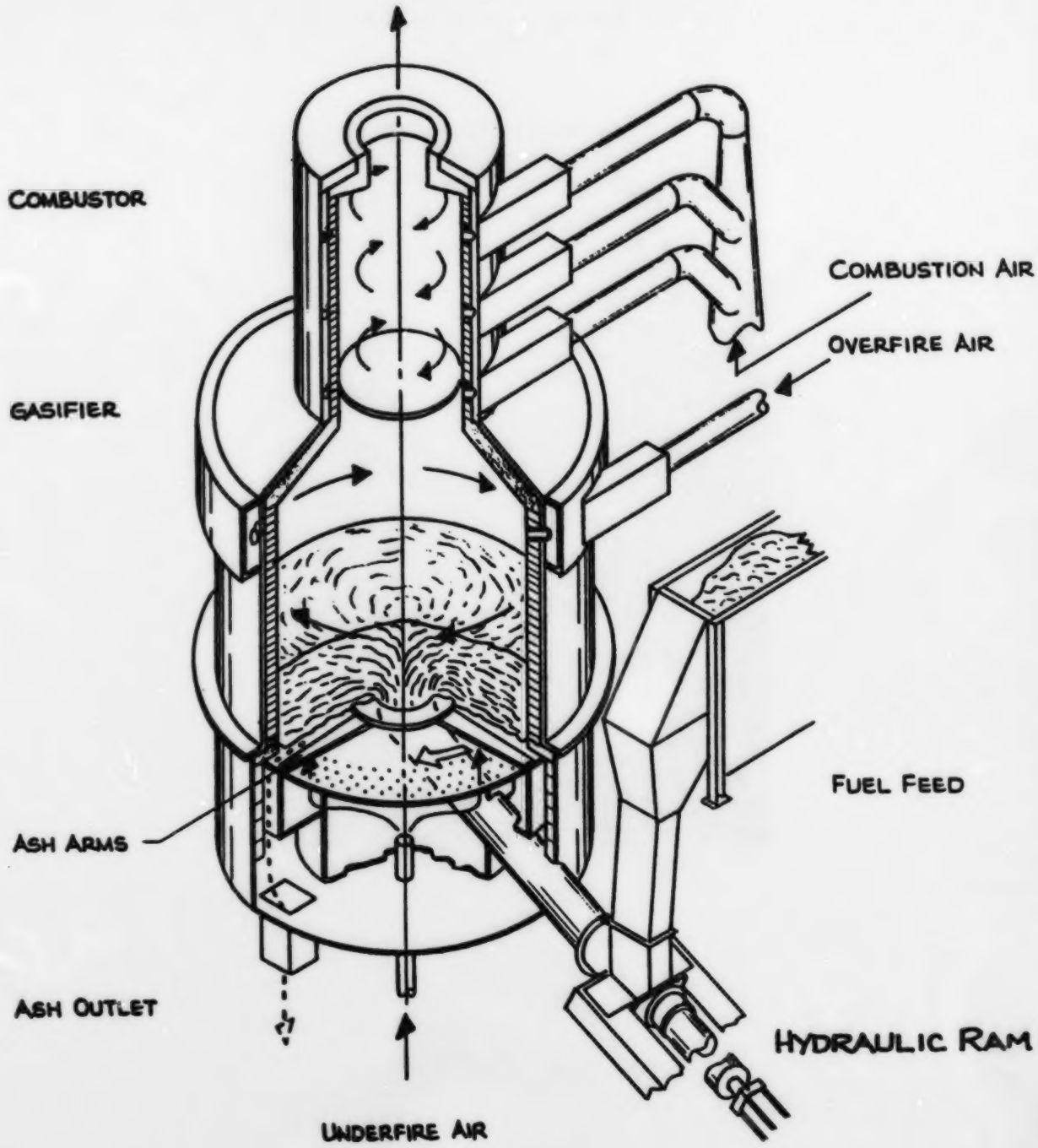
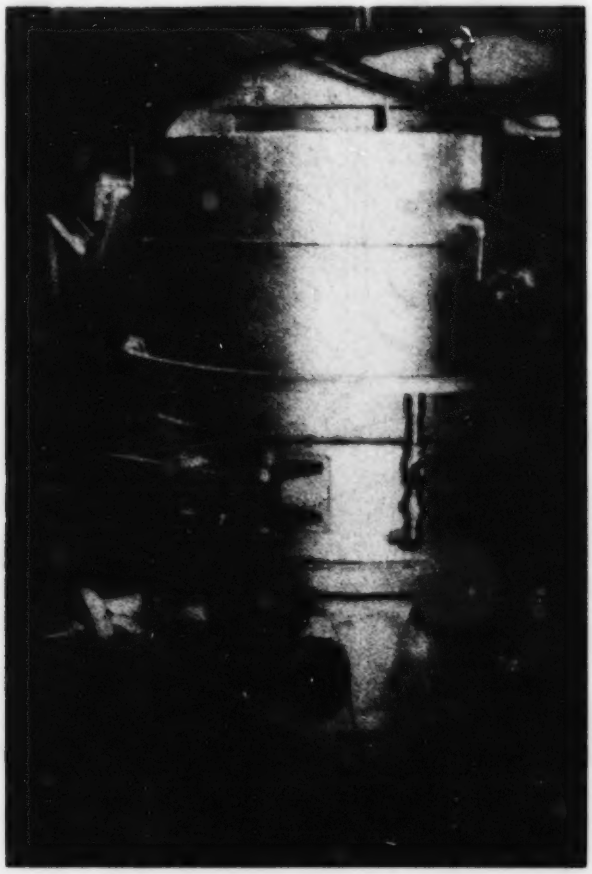


FIGURE 3 -- LAMB 0.9m DIAMETER TEST UNIT,

PRIMARY CHAMBER AND ASH CHAMBER



1.1 Objectives

In order to determine the optimum gasifier/combustor design for the milled peat fuel available at the Shippegan site, the objectives of the project were established as follows:

(1) Technical review of established hardware and literature.

(2) Laboratory analysis of specific physical, chemical and combustion parameters of the subject peat.

(3) Design and rework of the pilot-scale gasifier, and incorporation of test equipment.

(4) Testing, modification and evaluation of the pilot unit to develop constituent parts and derive a firm design basis for full-scale application.

(5) Documentation and Final Report.

1.2 Previous Work and Literature Review

1.2.1 Peat Technology

Comprehensive reviews of peat technology are presented by several authors in the 1979, 1980 and 1981 Symposia "Peat as an Energy Alternative", sponsored by the Institute of Gas Technology [1] [2] [3] . In particular, the papers by K. Leppa (1979, 1980, 1981) provide much practical information on the problems and design of peat handling and combustion.

1.2.2 Combustion

A review of peat combustion equipment in the relevant size range (up to 20-MW (70 GJ/h)) was presented at

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[1] Management Assessment of Peat as an Energy Resource, 1979

[2] Peat as an Energy Alternative, 1980

[3] Peat as an Energy Alternative 2, 1981

the 1984 International Peat Congress [4]. Grates have been used for sod peat, and grates, cyclone and fluidized bed systems have been used for milled peat. Cyclone systems were stated to be unsatisfactory due to ashing and slag formation problems. Mechanical inclined grates and fluidized bed systems were considered most appropriate for the combustion of milled peat. Underfed and conical grates were rated "suitable with restrictions." The importance of refractory in the drying of fuel on the grate and in control of slag formation was emphasized. The Lamb system is underfed and the grate is mechanically swept and agitated and may be considered equivalent to a mechanical inclined grate.

Circulating fluid beds have found considerable application in the combustion of milled peat. A demonstration of the Pyroflow (Ahlstrom) system is reported involving a retrofit to a Lamont bark boiler rated at 15-MW(54 GJ/h) (thermal output) [5]. Such systems operated at or above minimum transport velocity (approx. 0.3m/sec), and fine particulate is carried over by the gas to a hot cyclone which returns a portion of the gas, plus captured particulate, to the bottom of the bed. The high residence time and turbulence ensure good combustion efficiency and low excess air operation. The system operated with a high fluidizing velocity of 3m/sec.

Pilot plant and commercial unit fluidized bed tests were performed by Energy Incorporated in 1981 [6]. In the commercial test a 4.26m diameter Fluid Flame fluidized bed unit with an integral, top-mounted water tube boiler was fired with milled peat for 2.5 hours. The boiler produced an average of 7256 kg/h steam flow. Moisture content of the peat was between 29.1 and 30.7% (wet basis). Grain loading was 1217 mg/m3 at 17.7% oxygen. Sampling took place upsteam from the

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[4] Seppala, R. Peat Combustion Equipment for Block and District Heating Stations. Proceedings, 7th International Peat Congress. Dublin, Ireland, 1984.

[5] Yip, H., Engstrom, P. Peat Combustion in a Circulating Fluid Bed. Proceedings, 6th International Peat Congress, Duluth, Minnesota, 1980.

[6] Apa, R.P., Kuhl, R.D., Fluid-Bed Combustion of Peat with Energy Recovery: Demonstration Test Results. Peat as an Energy Alternative 2, 1981, Arlington, Va.

medium efficiency scrubber. The bed was fed from above by a single drop chute.

1.2.3 Gasification

Gasification methods have been the subject of much research and may be divided into pressurized and non-pressurized categories, of which the latter is of prime interest to this application. The efficiency of gasification increases with increased pressure due to the favorable shift in equilibrium of methane reactions. In the former category may be included the highly successful IGT PEATGAS ® Project which demonstrated conversion of 50 Tons/day of 10% moisture content peat to about 14 150 m3 of synthetic natural gas [7]. The process gasifier operated at 3.447 MPa pressure, and temperatures in the char gasifier fluidized bed were between 585 and 865°C. Gasifier superficial velocity was limited to 0.3m/s. Carbon conversion was shown to improve with higher temperatures and higher steam to carbon ratios.

Non-pressurized systems have been investigated as follows:

Co-current (downward) gasification was investigated by Jantunen, Wilen and Asplund [8]. The results indicated that peat with up to 50% moisture content was suitable as the raw material for gasification. Steam was recommended for dry fuels to avoid molten ash problems, though this was not found necessary for the wet sod peat used. Fuel was fed through an upper air lock and air introduced at the bottom of the pile. The sides of the vessel were tapered to accomodate the substantial reduction in volume as the fuel was dried and pyrolized. Air was introduced at the narrowed section and the importance of uniform temperature distribution and constant air feed rate was emphasized to avoid tar and melt clinker formation.

Both co-current and counter-current gasification in fixed beds were investigated at the Technical Research

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[7] Biljettina, R., Punwani, D.V., Status of the Peatgas Development Program Symposium Papers, Conference on Peat as an Energy Alternative, Arlington, Va, 1981

[8] Jantunen, M., Wilen, C. and Asplund, D. Co-current Gasification of Peat in a Fixed Bed. Proceedings, 6th International Peat Congress. Duluth, Minnesota, 1980.

Centre of Finland [9]. The feasibility of scale-up is greater with counter-current gasifiers since the reduction area in co-current gasifiers cannot be increased without permitting uncracked tars to exit with the gas stream. In addition, the higher inherent temperatures in the reduction zone led to ash melting problems which can be controlled in counter-current gasifiers by reduced air rates or steam addition. However, the gas quality in co-current flow is higher. The primary chamber of the Lamb unit is similar to a counter-current gasifier.

Sod peat of 30, 40 and 50% moisture content was used in the experiments and produced stable operation. In co-current gasification, a high proportion of fines (up to 50%) can be tolerated, but higher proportions clogged the process. The effect of fines in counter-current flow was not examined. For counter-current flow a maximum moisture content of 40% was indicated for good gas quality.

Fluidized bed gasification was investigated at the same location (the Technical Research Centre of Finland) by Salo, Filen and Asplund [10]. Preliminary tests at a laboratory scale involved cold air modelling of particulate elutriation from the bed, and at 25°C., curves were developed of weight loss vs. flow velocity in the bed. The curve is illustrated in Fig. 4. The weight loss was high relative to gas velocities, confirming a requirement for particulate recycling. The tests were performed with velocities between 0.2 and 0.9 m/s. In order to maintain gas quality, the peat moisture content should not exceed 15% wet basis and air should be pre-heated to 300°C.

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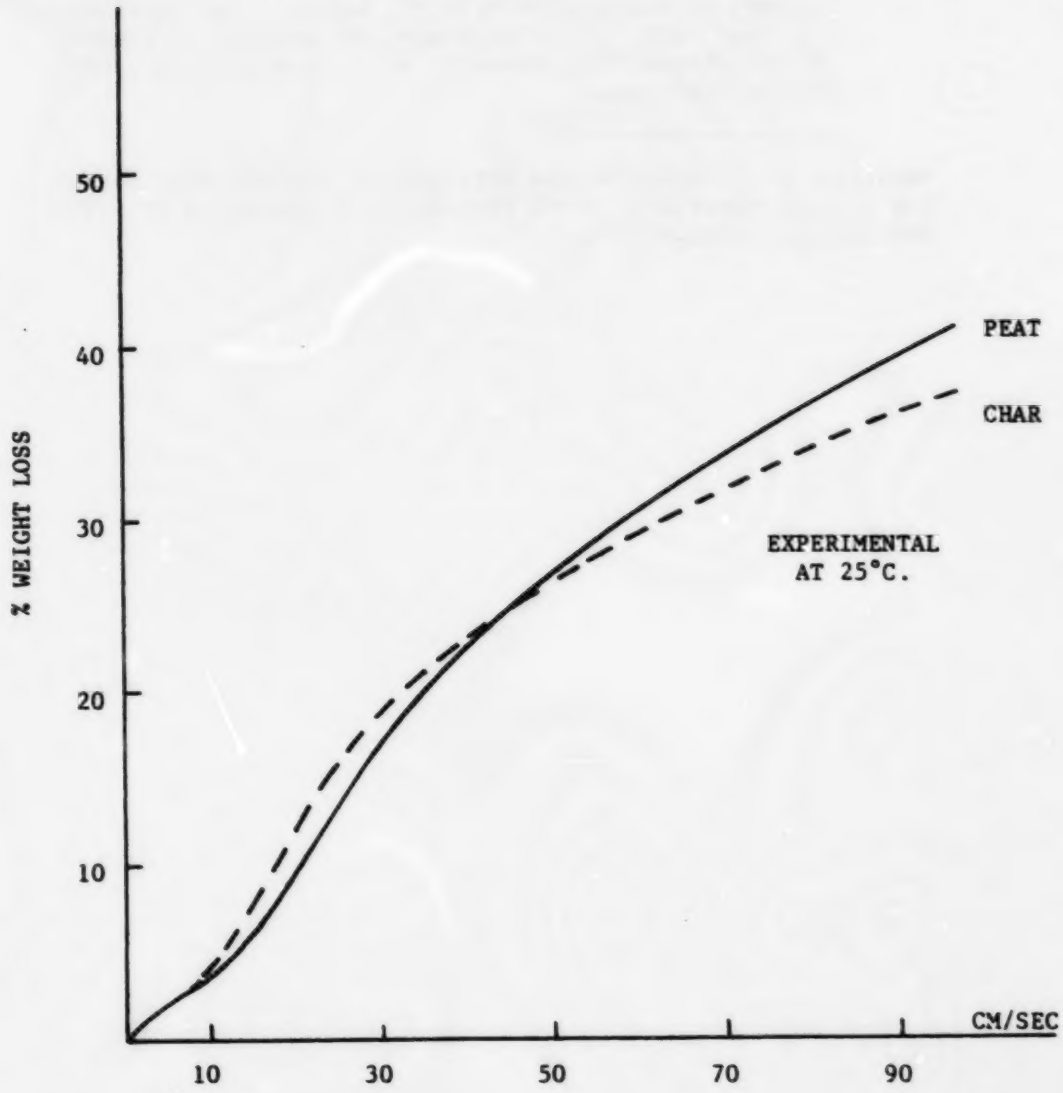
[9] Salo, K., Jantunen, M. and Asplund, D. Production of Fuel Gas with Gasification of Peat in Fixed Bed. Peat as an Energy Alternative, IGT, Arlington, Virginia, 1980.

[10] Salo, K., Filen, H. and Asplund, D. Gasification of Milled Peat on a Fluidized Bed. 6th International Peat Congress. Duluth, Minnesota, 1980

FIGURE 4 -- WEIGHT LOSS FROM FUEL BED



WEIGHT LOSS AS A FUNCTION OF FLOW RATE

1.2.4 Fuel Handling

Techniques for fuel handling are reviewed in the above-mentioned symposia papers and have been the subject of discussions with K. Leppa. In addition, bin and silo design have been the subject of studies at B.C. Research by Bundalli et al, and provide useful design information [11].

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[11] Bundalli, N., Morgan, D. and Martinez, O. Bin and Silo Design for Biomass Materials, ENFOR Project C-130 Report, Sept, 1983 DSS Contract 43SS.KN107-2-4177.

2.0 DEVELOPMENT OF TEST BURNER FACILITY AND SHAKEDOWN TESTS

A process flow diagram is shown in Fig. 5, and components are described as follows:

2.1 Air Systems

Air was supplied from a single, centrifugal fan rated at 1.89 m3/s and 4.48 kPa delivery pressure. The flow was divided into four streams, underfire, primary (overfire), secondary (overfire) and blend. Flows were metered by orifices in each line and controlled by manual or actuated damper valves. Delivery pipe length was 30 diameters minimum for flow smoothing. Flows were monitored by means of manometers and transmitted to the Fluke continuous data logger.

The underfire air supply pressure was boosted by a second fan rated 1.18 m3/s at 3.98 kPa delivery pressure and controlled by a manual valve. Underfire air temperature was transmitted to the data logger. Underfire air entered the chamber below the grate.

The primary (overfire) air supply was controlled by a manual valve. The primary air enters the primary chamber jacket and is directed to the combustion space by tangential nozzles in the refractory lining.

The secondary (overfire) air supply was controlled according to burner exit temperature by means of an actuated damper. The secondary air enters the secondary chamber of the burner by means of two tangential plenums, each equipped with manual dampers for further control. A small proportion of the secondary air was diverted from the lower plenum to cool the flameholder supports.

In order to avoid the use of a refractory stack it was necessary to reduce the temperature of the exit gas to below 532° C. A transverse blend box was therefore added to the burner at the secondary chamber exit and provided with a quench air supply. This was controlled according to blend box exit temperature by means of an actuated damper and flow transmitted to the data logger. Orifices were calibrated by pitot traverse.

FIGURE 5 -- PROCESS FLOW DIAGRAM -- TEST UNIT

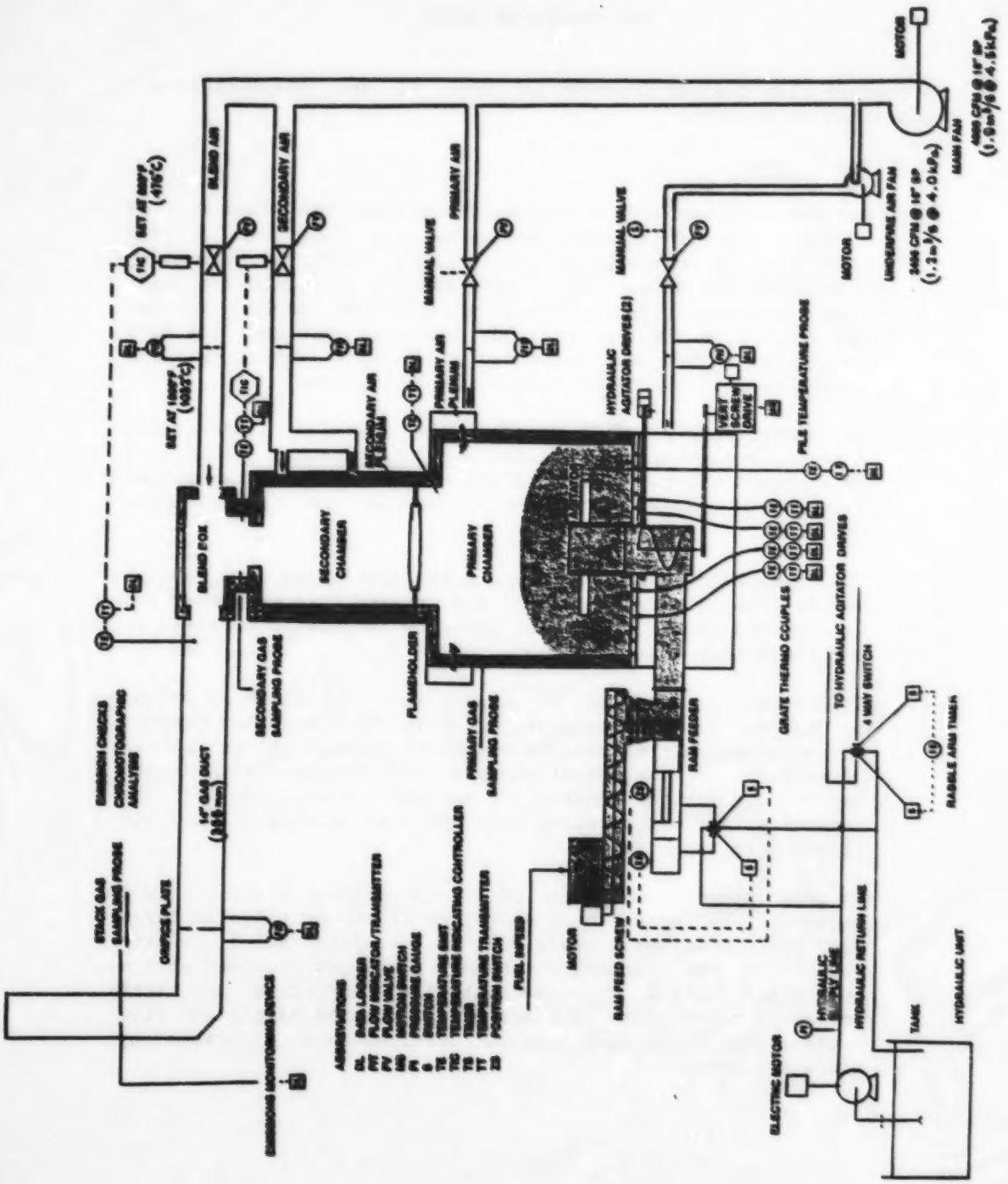
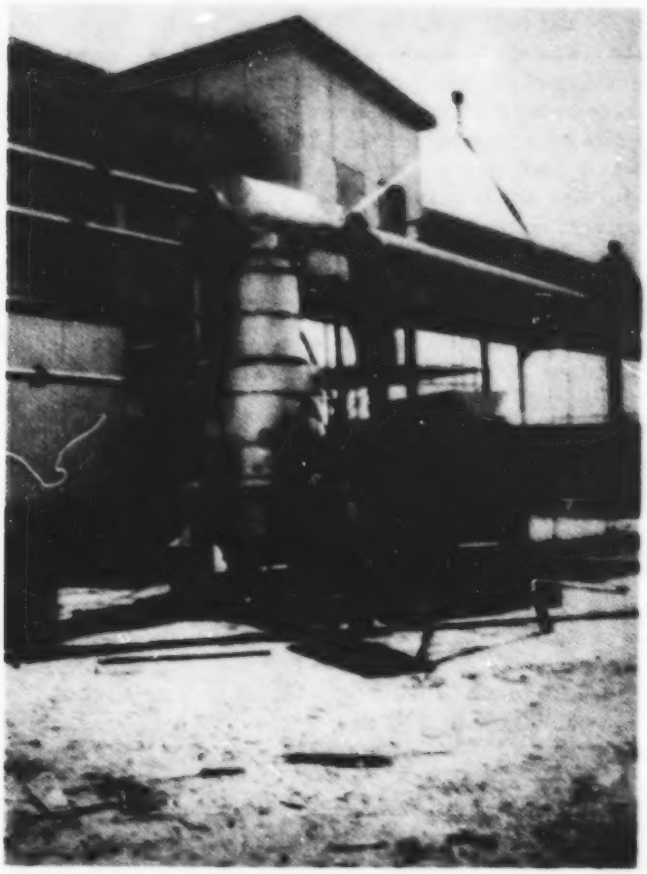


FIGURE 6 -- ASSEMBLY OF TEST UNIT



Note: Air lines left, Stack Gas right

2.2 Fuel Feed System

The fuel infeed system (Figs. 7, 8) comprised a 152mm variable speed screw dropping via a chute into a 152mm horizontal ram. The ram pushed the fuel to a transfer chamber beneath the grate where a 400 mm vertical screw pushed fuel into the pile. The end of the vertical screw was flush with the grate and an extension pipe with paddles was added during shakedown with a view to pre-drying the fuel and agitating the fuel pile. The extension pipe was made of stainless steel and was rotated slowly using a hydraulically operated ratchet mechanism. The variable speed screw, the ram and the feed tube agitator mechanism were hydraulically powered. The infeed rate was controlled at the horizontal screw. Base rate was set by means of a manual control valve and a parallel solenoid valve was energized according to the status of the OPCON fuel pile height controller. If the height dropped below the selected level, the infeed rate was increased until pile height was restored.

2.3 Gas Discharge System

Gas discharge from the blend box was controlled at 532° C. A 9m long x 356mm diameter steel exit pipe was equipped with an orifice plate to record gas flow and temperature. A 3.0m stack was equipped with sample ports for gas analysis and velocity measurements (Fig. 9).

FIGURE 7 -- FEED SCREW AND RAM

FIGURE 8 -- FEED SCREW

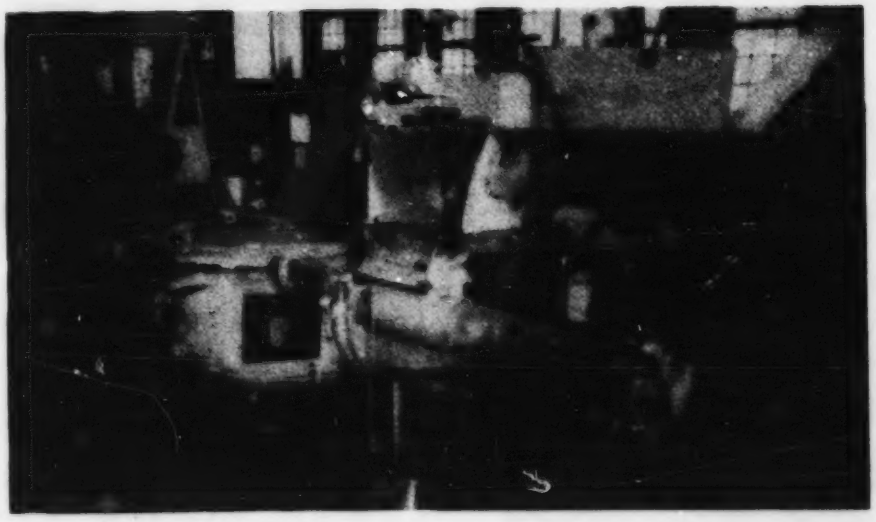
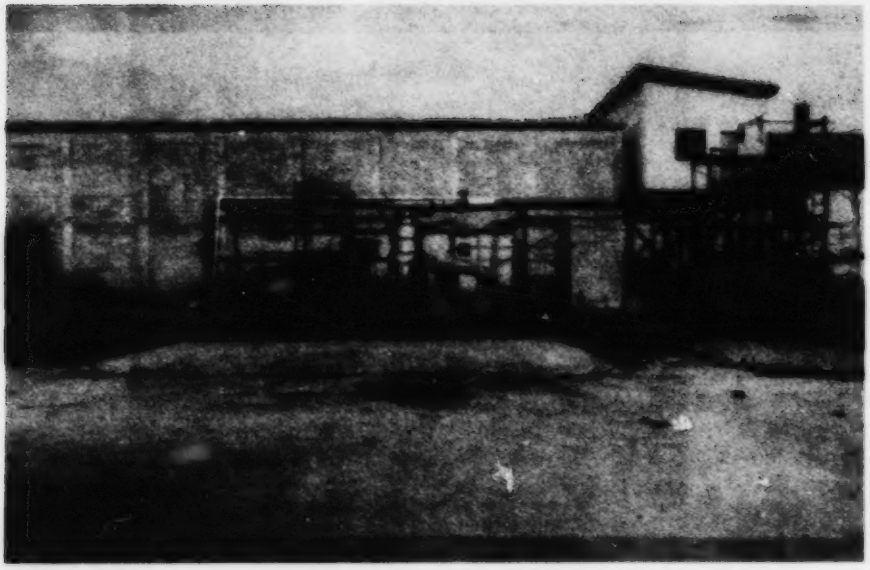


FIGURE 9 -- TEST UNIT ASSEMBLY



2.4 Gasifier/Combustor

The test burner comprised the following elements:

(1) An undergrate chamber housing the fuel infeed transfer system, vertical screw pipe and the ram pipe. Underfire air entered the chamber and was distributed to the pinhole grate.

(2) The primary chamber, above the pinhole grate. The refractory-lined chamber was 910mm in internal diameter and 762mm high, tapering to an outlet choke of 406mm and equipped with a ring of tangential nozzles in the upper part for air admission. The nozzles were 25mm in diameter and designed to promote swirl.

(3) The flameholder, consisting of a hollow disc of stainless steel and supported by three pipes. The pipes conveyed air from the secondary system to cool the flameholder.

(4) The secondary chamber which was refractory-lined and 406mm in internal diameter, with an outlet choke of 203mm diameter. The chamber was equipped with two rings of tangential nozzles for air admission and again designed to promote swirl. The amount of air distributed to each ring could be adjusted using dampers in the two inlet plenums. Height was 813mm to the choke.

(5) Temperature probes were attached to the grate, the upper primary and secondary chambers, the blend box exit and the hot gas orifice plate. These were Type K or Type R thermocouples and the signals were recorded on the data logger.

2.5 Shakedown Testing

The commissioning period provided valuable data and experience on the operation of the burner and is summarized in the comments which follow:

(1) Initial operation with hog fuel confirmed that the burner operated in the accepted gasification/combustion mode. The additional fan in the underfire line was added at this time to ensure that underfire pressure was adequate.

(2) It was observed that the sealing effect of hog fuel in the ram tube was less than with peat. On occasions

there would be smoke emissions with both fuels, dependent on the pile height in the primary chamber. This problem is not apparent on the commercial hog fuel units and can be attributed to the short length of the test unit feed tube. However, use of a rotary valve at some point in the feed system is recommended for isolation and safety.

(3) The peat fuel pile did not have the permeability of hog fuel and uniform underfire air distribution was not attained. Agitation of the pile was achieved using an extension tube attached to the rabble arm indexing mechanism. This was an improvement and had the added benefit of pre-drying the fuel and delivering it to the top of the pile.

(4) Limits to operation of the burner were discovered when peat of moisture content in excess of 65% was used. The pile formed into large lumps and burning was limited to char sites on the outside of the lumps.

(5) At moisture levels from 60% down to 35%, combustion was sustained with good stack opacity and temperatures in excess of 921° C. in both chambers. Primary chamber temperature was generally higher than secondary, indicating that at these output levels (up to 2.11 GJ/h), the gasification process was not pronounced. It appeared that heat release came from the combustion of particles entrained by the air. The underfire air tended to form into blowholes or to seek the periphery of the pile. However, this promoted adequate heat release in the chamber and burner output was comparable to hog firing.

(6) A cold air test was performed without combustion to examine the entrainment of particulate. The primary chamber was filled to approximately half height and increasing underfire air was fed to the system. An Environmental Systems Corporation P-5A Particulate Monitor was inserted into one of the stack ports. The monitor is sensitive to particulate in the range 0.2 to 10 microns. Infed fuel particulate distribution as measured by Econotech Limited was as follows:

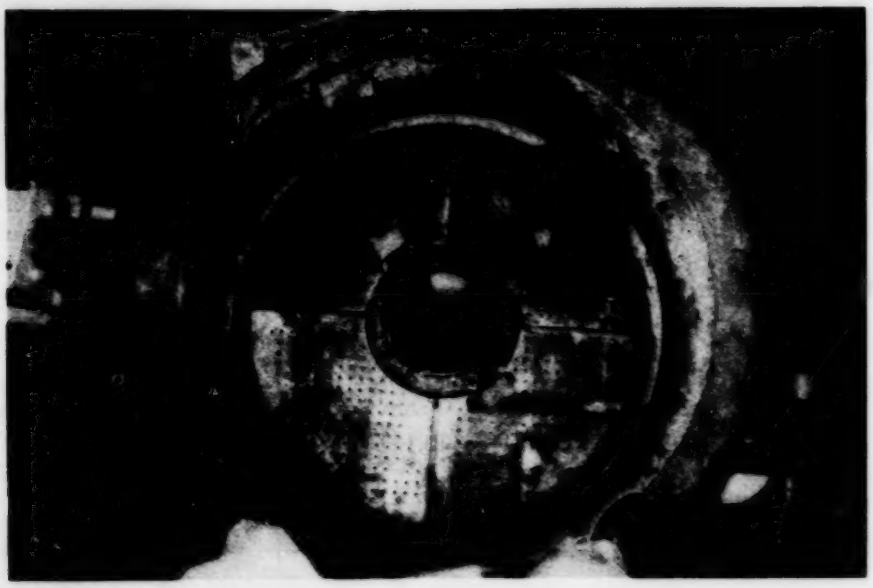
> 1680 microns/14.2%
> 840 microns/18.5%
> 420 microns/15.0%
> 250 microns/23.1%
< 250 microns/29.2%

It was observed that the fine particulate emissions increased sharply above a superficial primary chamber velocity of 0.3m/s. The fine particulate was accompanied by visible emissions as the velocity was increased, providing an indication of significant entrainment of fuel from the bed and confirming the elutriation illustrated by Fig. 2. Combustion of this particulate in the overfire spaces of the primary and secondary chambers is therefore an important consideration.

(7) Several burn tests were performed prior to formal performance testing. In all of these tests the components of the unit performed satisfactorily and problems were largely of a minor mechanical nature. It was necessary to determine optimal pile height and agitator length by trial and error methods, and these were finally set at 300mm and 400mm respectively.

(8) The ash discharge system (Fig. 10), comprised rabble arms which swept the grate surface and deposited ash into peripheral chutes. During later tests, the indexing mechanism for the rabble arms was used to drive the fuel agitator/feed tube and the rabble arms were removed. The build-up of ash during the course of the tests runs was not significant. The shakedown tests did show that the arms operated satisfactorily and the system would be capable of scale-up. The presence of a narrow bank of slag at the periphery of the grate following burndown is an indication that slag control by steam injection will be necessary for full-scale, sustained operation. The amount required could degrade combustion at the 55 to 60% moisture level.

FIGURE 10 -- GRATE AND RABBLE ARMS



3.0 -- PERFORMANCE TESTING

3.1 Test Methods

Test Procedures generally followed guidelines established by B.C. Research [12] . This requires the closing of mass and energy balances by means of accurate determination of input and output flows and temperatures.

3.1.1 Mass Balances

Input air flows were measured and logged.

Ash was subjected to analysis for design purposes but residual carbon was insignificant to the mass balances.

Fuel rate was measured by batch weighing before loading into the feed screw.

The particulate was subjected to thermogravimetric analysis for estimation of residual combustibles consisting of volatiles and fixed carbon. The sample was heated in nitrogen and ignited in oxygen.

Poor closure of the mass balances in some test cases cast suspicion on the air inlet flow measurements and in particular, the blend and secondary air pressure transducers. It was preferred to estimate these flows using internal mass and energy balances at the blend box. Adequate verification of such estimates was provided using the stack gas analysis, inlet and outlet blend box temperatures and burner outlet gas analysis.

3.1.2 Energy Balance

Burner output may be calculated without determining fuel mass flow, assuming that air flows, temperatures and fuel analysis are known and assuming that combustion is completed within the burner. Fuel consumption estimated by this method may be compared to measured consumption for verification. Thermal output at the stack was obtained from the stack temperature and gas analysis using enthalpy values. The heat loss from the delivery duct was calculated from the gas temperature drop between the blend box

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[12] Esplin, G., Aitken, M. A Workbook for Biomass Gasifier Sampling and Analysis, ENFOR Project C-172.

and the stack exit. Since this was a radiant loss it was confirmed using a hand-held infra-red thermometer.

The heat output from the blend box was stack output less radiant loss from the delivery duct. A heat balance was performed across the blend box to obtain burner output and compared with the output calculated from inflow parameters.

3.1.3 Gas Analysis

Gas analysis was considered of interest in the region above the primary chamber, at the exit from the secondary chamber and at the stack. Particulate sampling was also required at the stack.

Gas analysis was performed using a water-cooled stainless steel probe inserted into ports provided at each site. At the primary and secondary chamber sites, samples were drawn through three impingers. The first two impingers were water-filled to eliminate tars and particulate and to condense water vapour. The third impinger was empty for further vapour condensation prior to entry to a drying tower filled with silica gel. The sample was then drawn into a Tedlar bag and transported without delay to B.C. Research for gas chromatographic analysis.

In the stack, isokinetic sampling was required for accurate determination of particulate. The procedures generally followed those of Environment Canada for Source Testing [13] . The assembly consisted of a probe, pitot tube and thermocouple. The probe nozzles were changed according to the stack velocity to ensure isokinetic conditions at the probe inlet. The sample was drawn through a filter box maintained at 200°C. to prevent vapour condensation, thence via a flexible stainless tube to an impinger train. Since analysis for nitrogen oxides was required, the train consisted of two impingers filled with potassium permanganate, a third empty, and a final drying tower filled with silica gel. The sample was then drawn via the pump to a control box and into Tedlar bags for analysis.

3.1.4 Fuel Properties

Samples of fuel were subjected to analysis at

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[13] Standard Reference Methods for Source Testing: Measurement of Emissions of Particulates from Stationary Sources. Environment Protection Service.

Econotech Services Limited. Table 1 shows mean data on the fuel based on ten full ultimate analyses.

TABLE 1 -- FUEL ANALYSIS

Gross Calorific value	21.2 MJ/kg
Carbon, wt	49.5%
Oxygen, wt	41.7%
Nitrogen, wt	0.68%
Hydrogen, wt	5.81%
Sulphur, wt	0.14%
Ash, wt	2.17%
Ash Fusion Temperature	1200 +/- 10°C.
Cold pH (fuel)	4.1
Cold pH (ash)	10.5

3.1.5 Test Format

Performance test runs were of approximately one hour duration following a change of control settings. Three levels of fuel moisture content were used, 46%, 55% and 64% (wet basis). Fuel preparation consisted of solar drying to approximately 40% and re-addition of water to the required level. Fuel piles were covered with tarpaulins to prevent further drying and a sampling during tests showed moisture contents to be within +/- 2%.

Fuel samples were taken during the tests and analyzed for calorific value and moisture content.

Data logger scans were made every two minutes during test runs. Mean values of parameters were obtained from the data strip-outs.

3.2 Performance Tests

Sixteen tests were performed, fifteen with peat at various moisture levels and one with hog fuel as a comparison check. Of the fifteen peat tests, three were rejected as steady state observations following mechanical problems in the course of the run. The tests are considered in moisture content groupings as follows:

3.2.1 46% Moisture Content

Three tests were performed. Output gas surges were observed on the manometers coincident with indexing of the pile agitator and the process was highly sensitive to increases in underfire air flow; the associated increase in gas or volatile release in the pile was capable of producing severe particulate entrainment. Accordingly, underfire air was held at minimal levels and combustion rate controlled by overfire air rate. Estimated mass flows are given in Table 2. Table 3 shows the balance and closure of carbon and hydrogen. The stack gas analysis was applied to the burner exit and compared to the sampled analysis and the analysis calculated from fuel and inflow air data. These results are shown in Table 4. The energy balance compares observed sensible heat with net heat developed at the burner exit, calculated from the inflow parameters. This is given in Table 5.

TABLE 2 -- 46% M.C.

MASS FLOWS kg/h

Test Number	10	11	12
IN			
Underfire Air	208	115	153
Primary Air	344	445	353
Secondary Air	767	800	1453
Blend Air	1824	2083	2244
Fuel	172	188	289
Total	3315	3631	4492
OUT			
Stack Gas	3324	3635	4504

TABLE 3 -- 46% M.C.

ELEMENT BALANCE kg/h

TEST	ELEMENT	IN	OUT	%CLOSURE
10	Carbon	49.0	56.2	115%
	Hydrogen	19.5	18.6	95%
11	Carbon	51.2	64.9	126%
	Hydrogen	20.4	19.0	92.5%
12	Carbon	80.7	80.3	99%
	Hydrogen	308	25.4	83%

TABLE 4 -- 46% M.C.

BURNER EXIT GAS ANALYSIS

	PERCENT BY VOLUME DRY GAS		
	CO2	N2	O2
TEST 10			
From stack data	10.4	78.6	11.0
From sampling at exit	9.8	78.9	10.6
From inflow data	8.8	79.3	12.0
TEST 11			
From stack data	11.6	78.6	9.7
From sampling at exit	11.5	78.9	9.2
From inflow data	9.3	79.3	11.4
TEST 12			
From stack data	10.2	79.2	10.6
From sampling at exit	12.7	78.6	7.6
From inflow data	10.0	79.3	10.7

TABLE 5 -- 46% M.C.

ENERGY BALANCE

GJ/h -- Net or Lower Heat Basis			
	Test 10	Test 11	Test 12
Total energy in	1.55	1.72	2.65
Sensible heat at burner exit	1.63	1.83	2.75
% Closure	105%	106%	104%

3.2.2 55% Moisture Content

Mass Flows are shown in Table 6, Element Balances in Table 7, Gas Analysis Comparison in Table 8 and Energy Balance in Table 9. With this fuel, the burner gave stable operation. Output was again adjusted using overfire air flows.

TABLE 6 -- 55% M.C.

MASS FLOWS kg/h

Test Number		4	5	6	7	9
IN						
	Underfire Air	714	275	642	267	241
	Primary Air	324	307	119	436	490
	Secondary Air	547	955	140	500	105
	Blend Air	2985	2482	1317	1272	1509
	Fuel	290	253	150	147	163
Total		4860	4272	2368	2622	2508
OUT						
	Stack Gas	4897	4416	2369	2616	2516

TABLE 7 -- 55% M.C.

ELEMENT BALANCE kg/h

TEST	ELEMENT	IN	OUT	%CLOSURE
4	Carbon	72.6	98.9	136%
	Hydrogen	34.9	40.0	114%
5	Carbon	65.8	73.5	111%
	Hydrogen	31.7	30.0	94%
6	Carbon	33.6	39.5	117%
	Hydrogen	16.3	16.8	103%
7	Carbon	30.8	42.6	138%
	Hydrogen	15.9	12.7	80%
9	Carbon	37.6	48.5	129%
	Hydrogen	18.1	15.4	85%

TABLE 8 -- 55% M.C.

BURNER EXIT GAS ANALYSIS

	PERCENT BY VOLUME DRY GAS		
	CO2	N2	O2
TEST 4			
From stack data	16.5	79.4	6.9
From sampling at exit	14.0	80.0	6.5
From infow data	11.0	79.3	9.6
TEST 5			
From stack data	10.9	77.7	11.4
From sampling at exit	15.0	77.2	6.3
From inflow data	9.9	79.3	10.8
TEST 6			
From stack data	10.8	78.8	10.4
From sampling at exit	17.5	79.4	1.87
From inflow data	9.1	79.2	11.7
TEST 7			
From stack data	8.6	76.7	14.7
From sampling at exit		No Data	
From inflow data	6.7	79.2	14.1
TEST 9			
From stack data	13.9	79.7	6.4
From sampling at exit	10.1	78.5	10.4
From inflow data	11.1	79.3	9.5

TABLE 9 -- 55% M.C.

ENERGY BALANCE

GJ/h Net or Lower Heat Basis

Test No:	4	5	6	7	9
Total heat in	2.06	1.75	1.05	1.07	1.11
Sensible heat at burner exit	2.44	2.15	1.11	1.06	1.21
%Closure	112%	116%	100%	94%	103%

3.2.3 64% Moisture Content

Mass flows are given in Table 10, Element Balance and Closure in Table 11, Gas Analysis Comparisons in Table 12 and Energy Balance in Table 13. These tests were performed at the limit of ignition of the gases in the primary chamber. Again tests were performed with little underfire air and varying amounts of overfire air.

TABLE 10 -- 64% M.C.

MASS FLOWS kg/h

Test Number	13	14	15
IN			
Underfire Air	115	115	117
Primary Air	485	420	308
Secondary Air	251	507	468
Blend Air	1471	1523	1287
Fuel	218	236	215
TOTAL	2540	2801	2397
OUT			
STACK GAS	2562	2818	2415

TABLE 11 -- 64% M.C.

ELEMENT BALANCE kg/h

TEST	ELEMENT	IN	OUT	%CLOSURE
13	Carbon	93	97	104%
	Hydrogen	56	57	102%
14	Carbon	99	115	116%
	Hydrogen	59	73	124%
15	Carbon	92	92	100%
	Hydrogen	55	60	109%

TABLE 12 -- 64% M.C.

BURNER EXIT GAS ANALYSIS

Percent by Volume Dry Gas

	CO2	N2	O2
TEST 13			
From stack data	12.7	79.1	8.2
From inflow data	11.7	79.3	8.9
TEST 14			
From stack data	13.0	79.1	7.8
From inflow data	10.2	79.3	10.5
TEST 15			
From stack data	11.6	79.2	9.1
From inflow data	10.9	79.3	9.8

TABLE 13 -- 64% M.C.

ENERGY BALANCE

Net or Lower Heat Basis GJ/h

	Test 13	Test 14	Test 15
Total Heat In	1.11	1.19	1.10
Sensible Heat at Exit	1.18	1.29	1.19
% Closure	107%	108%	109%

3.2.4 Emissions

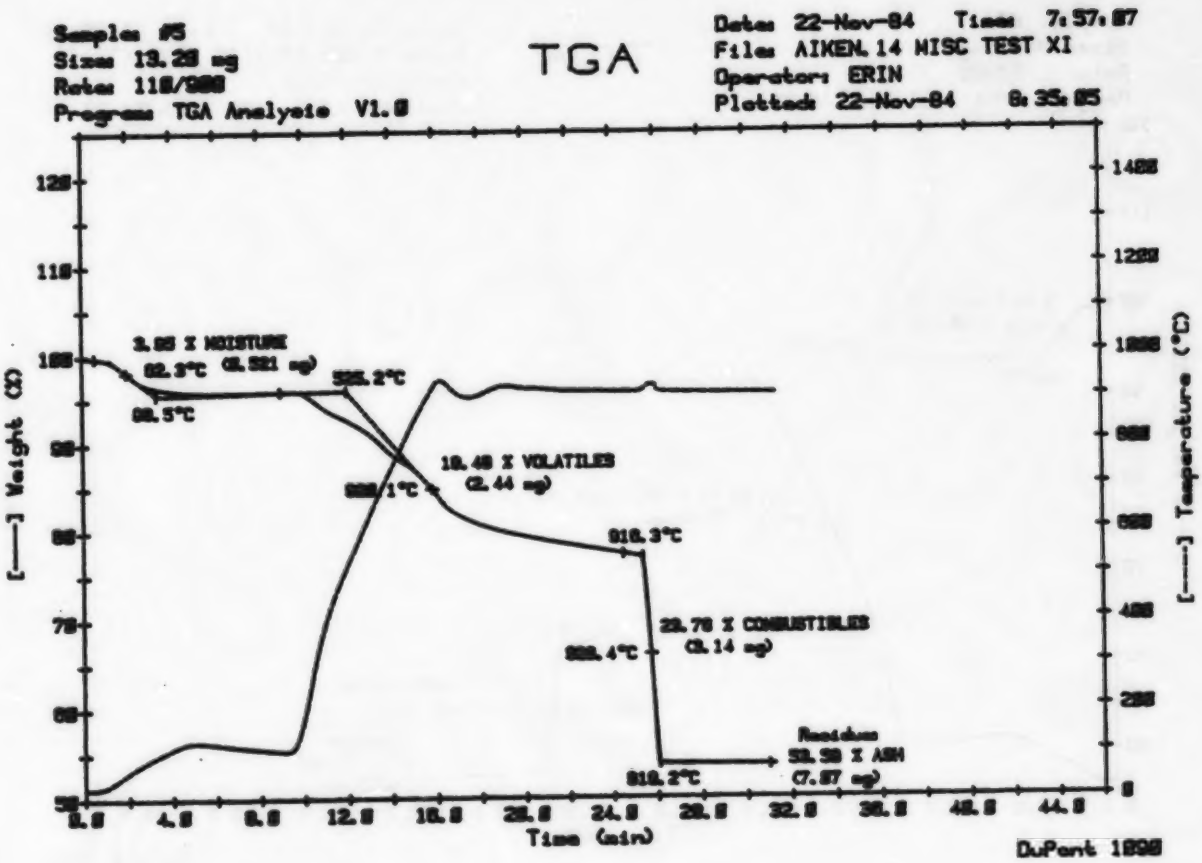
Stack Particulate and NOx emissions are presented in Table 14. The stack plume was clean under steady state conditions.

TABLE 14 -- EMISSIONS

		PARTICULATE			NOx
TEST	FUEL	gr/scf	kg/h	mg/m3	mg/m3
2	Hog, 55% M.C.	.065	.31	150	17.8
4	Peat, 55% M.C.	.307	2.6	703	75.2
5		.194	1.5	445	63.2
6		.431	1.8	986	43.3
7		.131	0.6	299	38.8
9		.086	0.4	196	12.6
10	Peat, 46% M.C.	.211	1.3	482	77.3
11		.118	0.7	270	66.5
12		.182	1.4	416	136.8
13	Peat, 64% M.C.	.084	.4	192	44.0
14		.589	2.8	1347	44.8
15		.446	1.8	1020	46.1

The particulate was subjected to thermographic analysis to determine proportion of residual combustibles. Thermographs are presented for Tests 5, 7, 9, 11, 13 and 15 in Figures 11, 12, 13, 14, 15 and 16.

FIGURE 11 -- PARTICULATE THERMOGRAPH -- TEST 5



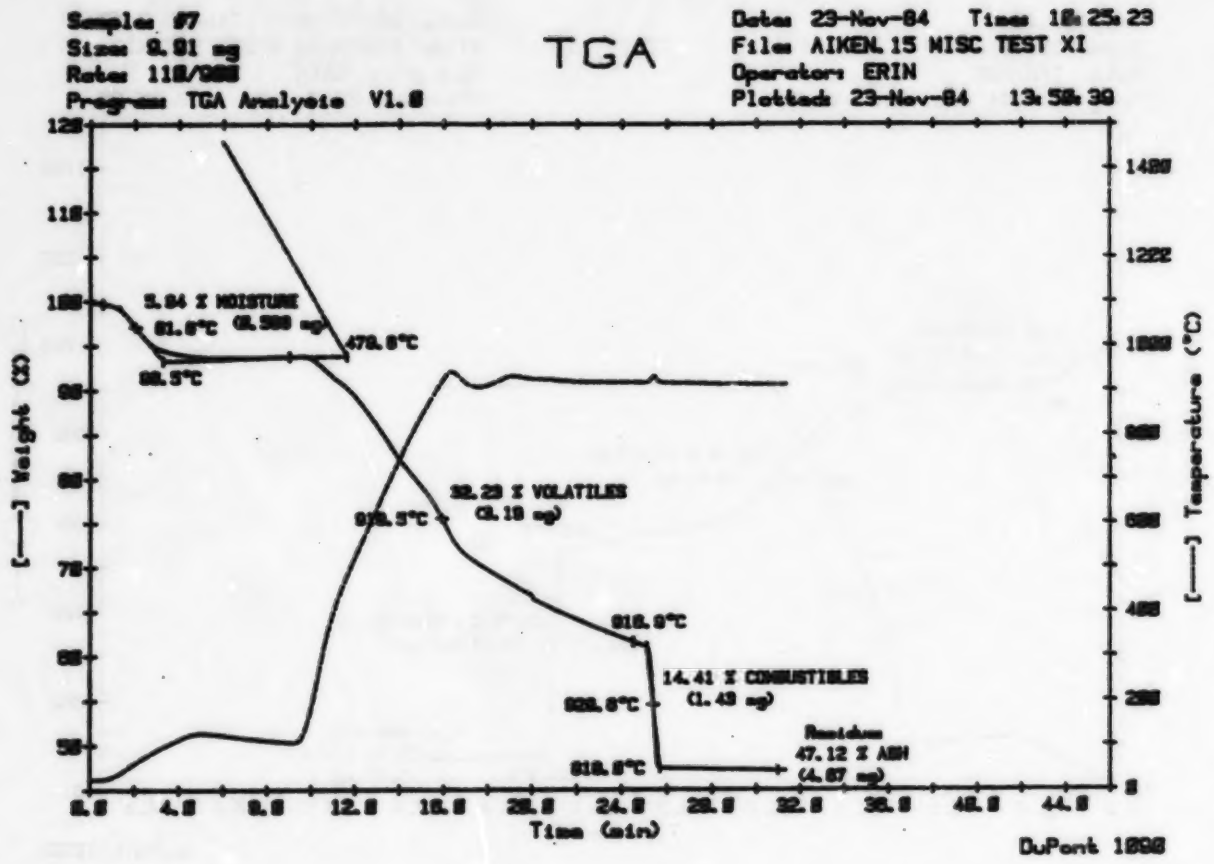
Sample: #5
Size: 13.28 mg
Rate: 11B/99B
Program: TGA Analysis V1.B

Date: 22-Nov-84 Time: 7:57:07
File: AIKEN.14 MISC TEST XI
Operator: ERIN
Plotted: 29-Nov-84 18:58:36

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		82.3	98.5	0.52	3.95
VOLATILES	525.2	928.1		2.44	18.48
COMBUSTIBLES	918.3	928.4	918.2	3.14	23.76
ASH		Residue at 999.7 °C		7.07	53.39

Modified Sample Weight: 13.28 mg

FIGURE 12 -- PARTICULATE THERMOGRAPH -- TEST 7



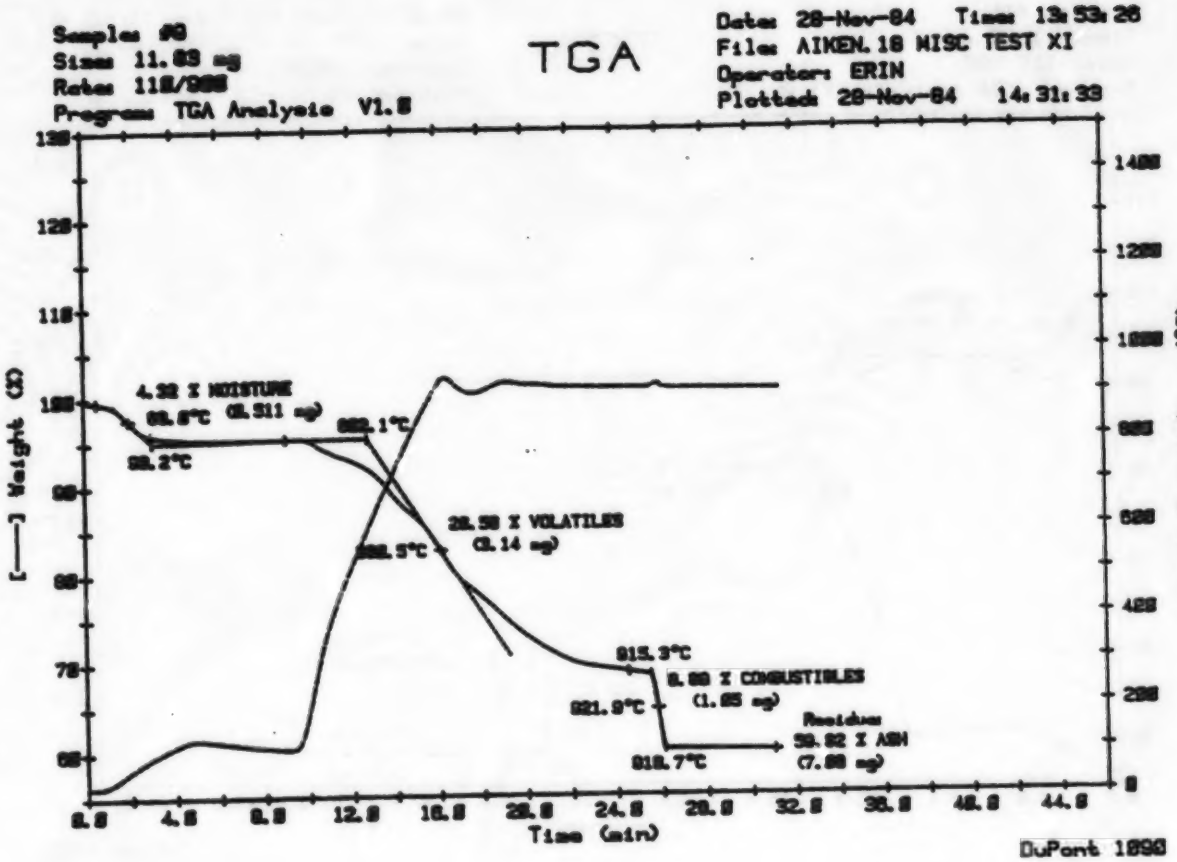
Sample: #7
Size: 9.91 mg
Rate: 11B/98B
Program: TGA Analysis V1.B

Date: 23-Nov-84 Time: 18:25:23
File: AIKEN.15 MISC TEST XI
Operator: ERIN
Plotted: 23-Nov-84 15:23:13

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	[%]
MOISTURE		81.6	98.5	0.59	5.94
VOLATILES	479.8	919.5		3.19	32.23
COMBUSTIBLES	918.9	929.6	918.8	1.43	14.41
ASH	Residue at 912.6 °C			4.67	47.12

Modified Sample Weight: 9.91 mg

FIGURE 13 -- PARTICULATE THERMOGRAPH -- TEST 9



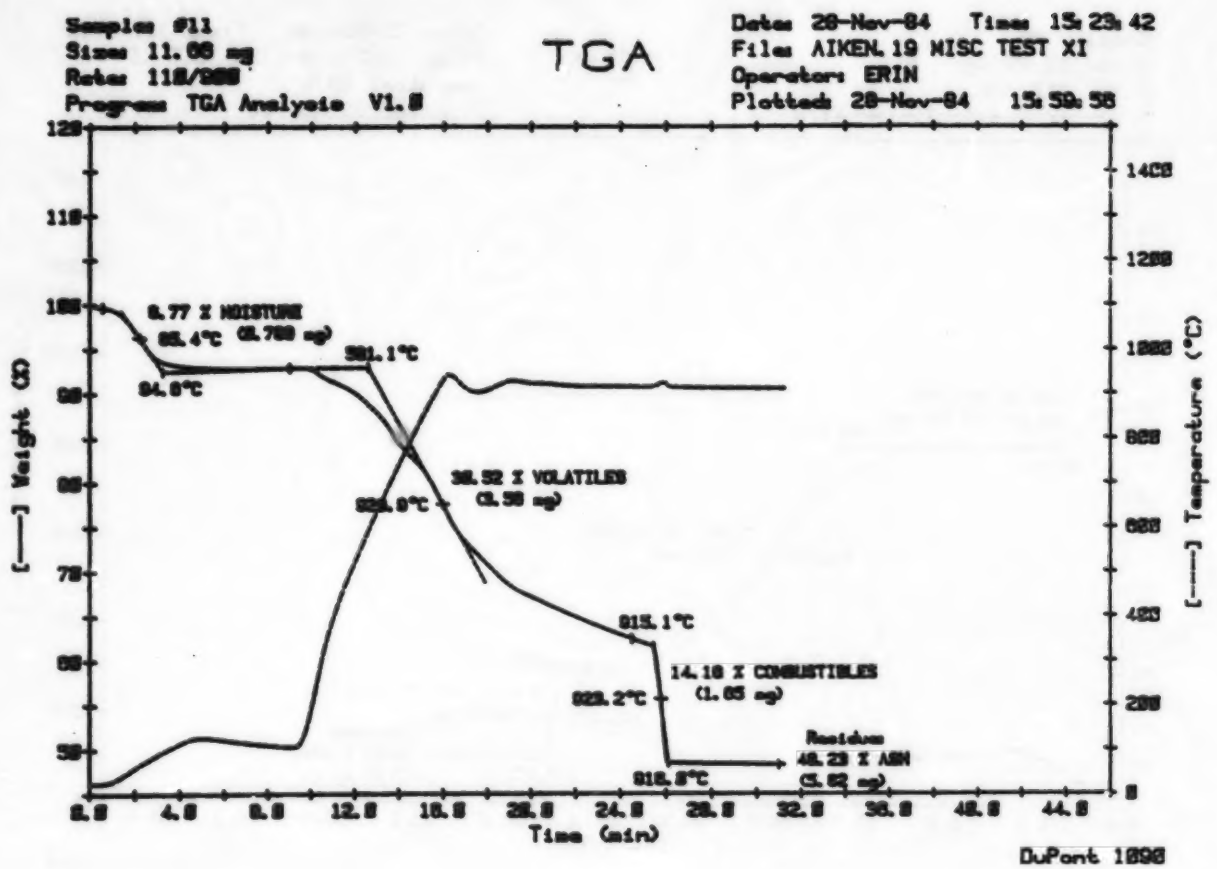
Sample: #8
Size: 11.83 mg
Rate: 11B/90B
Program: TGA Analysis V1.B

Date: 28-Nov-84 Time: 13:53:26
File: AIKEN.18 MISC TEST XI
Operator: ERIN
Plotted: 28-Nov-84 14:51:19

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		88.8	99.2	8.51	4.32
VOLATILES	882.1	938.5		3.14	28.58
COMBUSTIBLES	915.3	921.9	918.7	1.85	8.89
ASH		Residue at 911.2 °C		7.88	59.82

Modified Sample Weight: 11.83 mg

FIGURE 14 -- PARTICULATE THERMOGRAPH -- TEST 11



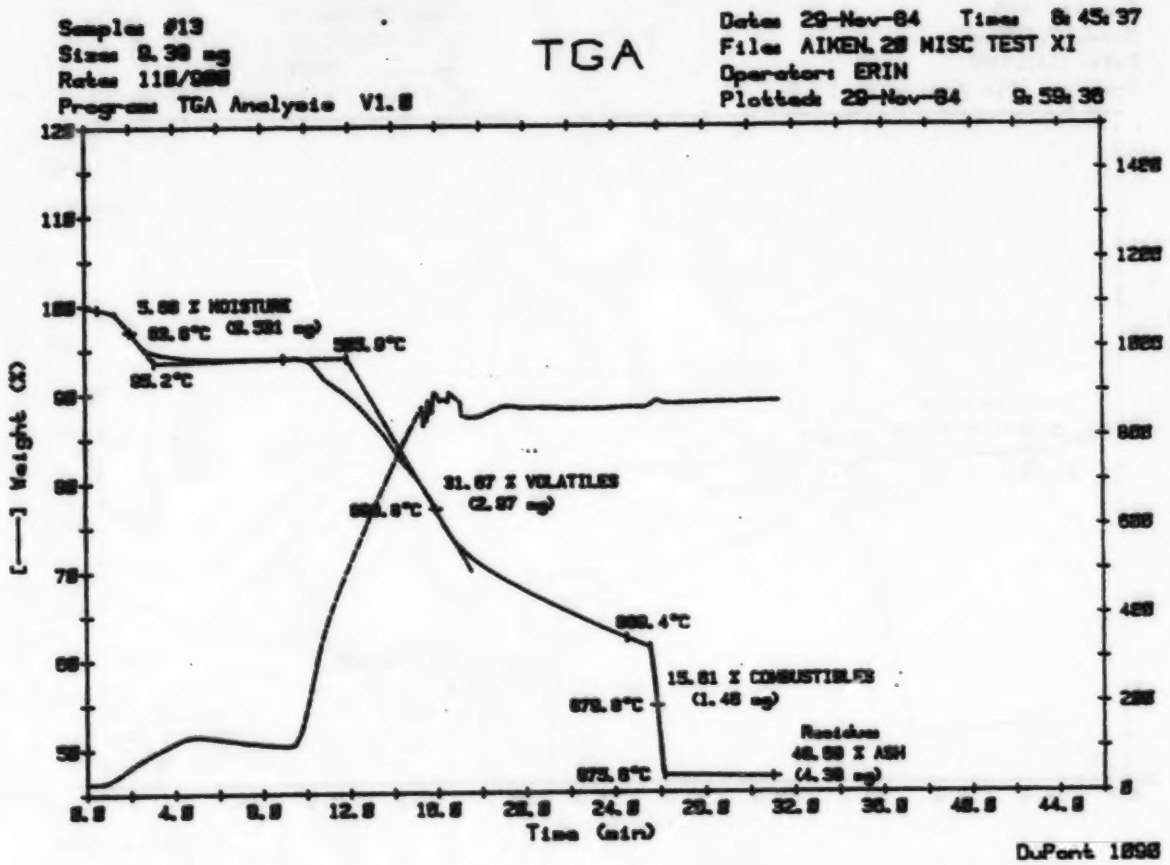
Sample: #11
Size: 11.68 mg
Rate: 11B/98B
Program: TGA Analysis V1.B

Date: 28-Nov-84 Time: 15:23:42
File: AIKEN.19 MISC TEST XI
Operator: ERIN
Plotted: 28-Nov-84 16:05:33

Transition	Onset (°C)	Inflection (°C)	Completion (°C)	Weight (mg)	Weight (%)
MOISTURE		85.4	94.8	8.79	8.77
VOLATILES	591.1	923.9		3.58	38.52
COMBUSTIBLES	915.1	923.2	918.9	1.65	14.18
ASH	Residue at 918.9 °C			5.62	48.23

Modified Sample Weight: 11.68 mg

FIGURE 15 -- PARTICULATE THERMOGRAPH -- TEST 13



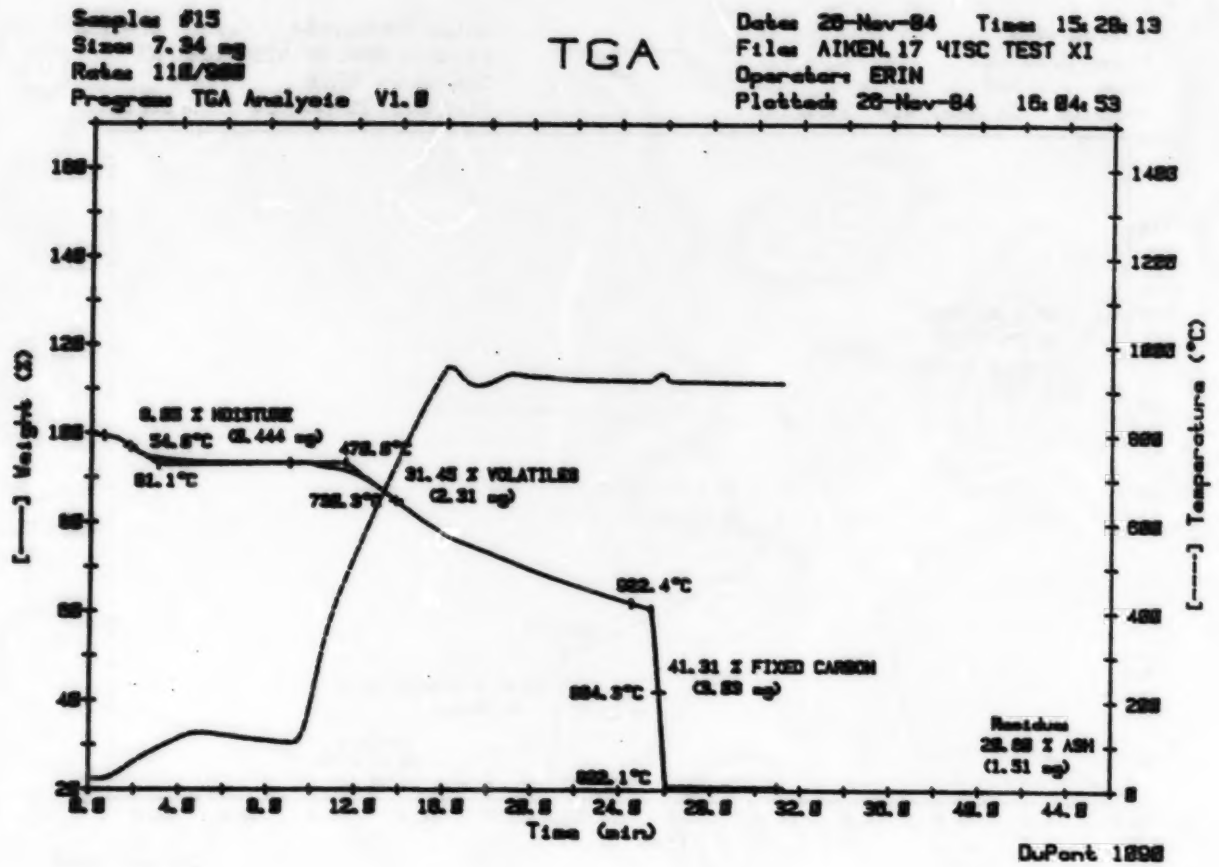
Sample #13
Size 9.38 mg
Rate 10°/min
Program: TGA Analysis V1.0

Date: 29-Nov-84 Time: 8:45:37
File: AIKEN.28 MISC TEST XI
Operator: ERIN
Plotted: 29-Nov-84 10:22:24

Transition	Onset (°C)	Inflection (°C)	Completion (°C)	Weight (mg)	Weight (%)
MOISTURE		83.6	95.2	0.53	5.68
VOLATILES	385.9	808.8		2.97	31.67
COMBUSTIBLES	869.4	879.8	875.6	1.46	15.61
ASH		Residue at 888.1 °C		4.38	48.69

Modified Sample Weight: 9.37 mg

FIGURE 16 -- PARTICULATE THERMOGRAPH -- TEST 15



Sample #15
Size 7.34 mg
Rate 10/900
Program TGA Analysis V1.0

Date: 28-Nov-84 Time: 15:28:13
File: AIKEN.17 MISC TEST XI
Operator: ERIN
Plotted: 28-Nov-84 16:22:41

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	[%]
MOISTURE		54.8	91.1	8.44	8.85
VOLATILES	478.8	738.3		2.31	31.45
FIXED CARBON	922.4	884.3	922.1	3.03	41.31
ASH	Residue at 915.3 °C			1.51	28.88

Modified Sample Weight: 7.34 mg

4.0 TEST CONCLUSIONS AND DESIGN RECOMMENDATIONS

4.1 Combustion Process

4.1.1 Conclusions

The test unit demonstrated stable combustion of milled peat fuel whose moisture content varied from 46% to 64%. Maximum outputs achieved during these tests were 2.75 GJ/h with 46% M.C. fuel, 2.44 GJ/h with 55% M.C. fuel and 1.29 GJ/h with 64% M.C. fuel. These correspond to grate heat release rates based on net grate area of 4.54, 4.01 and 2.12 GJ/m2. The 50% reduction in load due to the increase in peat moisture content from 55% to 64% indicates a high sensitivity to fluctuations above the 55% level. Control of fuel quality in terms of GJ/m3 and moisture is recommended, an on-line moisture meter should be included.

Particulate emissions at the stack varied from 196 mg/m3 (0.084 gr/scf) to 1347 (0.589 gr/scf) and stack opacity was excellent under steady-state operation. Grain loadings compare favourable to full-scale fluidized bed tests [6] by other investigators. However, at upper grain loadings, "char sparklers" could be emitted.

Interpretation of emission test results must account for dilution by quench air in the blend box; particulate loadings from the burner exit as opposed to the stack are certainly higher. The thermographic analysis showed that a high proportion (30-50%) of the particulate consisted of combustible fixed carbon and volatiles. The volatiles consist of hydrocarbons which have condensed on the char particles in the blend box.

Stack NO emissions are in the region of 12.6 to 136.8 mg/M3, equivalent to 0.05 to 0.41 lb/million BTU. These values may be higher at the burner exit, but nevertheless remain low compared to reported results for spreader-stoker systems. Recent work [14] has shown that local oxygen availability is the controlling parameter for NO formation in bed or

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[14] Munro, J.M., Bradshaw, F.W., Pershing, D.W. Control of Pollutant emissions from Coal and Wood Combustion in Spreader-Stoker Systems. Intl. Symposium on Conversion to Solid Fuels, American Flame Research Cttee, Newport Beach, California, 1982.

suspension stages and that NO formation may be reduced using sub-stoichiometric conditions. Such conditions exist in the tested system and may represent an advantage over high velocity fluidized bed systems with excess oxygen.

The combustion process in the test unit may be compared with the normal operation of the Lamb Combustor on wet hog fuel, as follows:

1. Underfire air did not uniformly percolate the fuel pile despite installation of an agitator. Combustion could be sustained with minimal or zero underfire air. Surges were observed with small changes in underfire air.

2. Grate temperatures remained low throughout the tests indicating a lower proportion of char burnout on the grate.

3. Positive closures of the mass and energy balances in most cases suggested a proportion of heat release had taken place within the blend box. The amount was generally between 3 and 9%. Gas analysis confirmed this by a consistently higher proportion of carbon dioxide observed than predicted by inflow parameters and conversely, a lower proportion of oxygen.

4. Gas analysis in the primary chamber outlet consistently showed stoichiometric or over-stoichiometric conditions and primary temperatures were generally higher than secondary.

The combustion process suggested by these observations is as follows:

1. Fuel is fed through the pile by the agitator tube. Partial drying occurs.

2. Fuel is fed to the top of the pile where further drying proceeds.

3. Particulate entrainment from the pile is dependant upon overfire air rate and flow of pyrolysis gases from the pile. Velocities correspond to reported values for the onset of "bubbling" fluidization.

4. A proportion of heat released above the pile is radiated back, to contribute to drying and pyrolysis.

5. Oxygen for exothermic pyrolysis reactions is supplied by overfire and underfire air. However, the fuel surface area available to the overfire air is self-limiting since it is blanketed by pyrolysis gases in counterflow. The reverse is true for underfire air. The high specific area of the fuel (27% by weight less than 250 microns), and co-current flow, imply that a rapid release of gas follows an increase in underfire air rate. In turn, this leads to disturbances in the pile, increasing the "bubbling" fluidization activity.

6. Particulate burns out above the pile in the primary or secondary chambers. Residual ash is retained in the burner by cyclonic action. In the case of the test unit, the design permits a proportion of the particulate to leave the burner and combust in the blend box.

7. Ash is removed from the burner from the bottom of the pile using rabble arms and airlocks in the conventional way.

4.1.2 Scale Up

In assessing the effects of scale up to a commercial 10 GJ/h unit, similarity criteria may be considered in the three areas of residence time, temperature and turbulence.

Superficial velocities and aspect ratios (diameter:height) are of the same magnitude and residence time is unlikely to increase substantially without design changes.

Closer control of air flows is possible in the full scale unit and secondary temperature may be increased by lower excess air operation. Primary temperature, normally controlled at 650-820° C., may be increased to improve radiant heating of the pile and burn-out of particulate.

Turbulence can be defined using the Reynolds Number based on superficial velocity for identical grate heat release in GJ/m2. Conditions are found to be similar in primary and secondary chambers. Reynolds numbers for the primary chamber are in the range 6,000 to 20,000 and for secondary, 30,000 to 50,000.

The similarity of swirl conditions may be considered in comparing the ratio of angular momentum contributed

by the tuyeres, to the axial momentum, both of which are conserved. The swirl number is defined [15]:

$$S = \frac{Ga}{Gx.R}$$

where Ga = angular momentum flux
Gx = linear (axial) momentum flux
and R = chamber radius.

For the same grate heat release, swirl in the full-scale unit primary chamber is greater by a factor of 3 to 5 than in the test unit and an improvement in particulate burn-out can be expected. The increased swirl is produced by higher velocities through the tuyeres.

In summary, increased combustion efficiency in the full scale units is predicted.

4.1.3 Design Recommendations

The process described above requires minimal adaptation of the Lamb design. In addition, the adaptations can easily be accomodated with existing units. Key factors are the restriction of the pile superficial velocities to values corresponding to low velocity fluidization and the provision of adequate burnout conditions for particulate. Recommendations are as follows:

1. Superficial velocity from the pile should not exceed 0.6m/s. Typical values for underfire air flow are calculated in Table 15, based on chamber diameter, fuel properties and output. Maximum suggested values of underfire air flow should not be exceeded.

2. Burner output should be controlled by underfire air flow to the maximum levels quoted. Primary air flow should be set to follow output and must be used as a boost to output when underfire air cannot be increased, by increasing turbulence and particulate burning. Consideration should be given to nozzle orientation for best effect.

3. Secondary air flow should control outlet temperature. Air distribution to the secondary

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[15] Beer, J.M., Chigier, N.A. Combustion Aerodynamics. Applied Science Publishers Ltd. 1972.

air nozzles should favour early mixing.

4. Pile depth should be kept lower than with hog fuel to provide maximum burn-out space and radiant surface. Increased chamber height should be considered.

TABLE 15 -- MAXIMUM UNDERFIRE AIRFLOW

Fuel M.C.%	Burner Dia m	Max Burner Output GJ/h	Max Underfire Air m3/min
45	1.82	8.9	11.9
	3.04	24.7	33.1
	4.27	48.4	64.9
55	1.82	7.8	10.4
	3.04	21.8	29.3
	4.27	42.7	57.3
65	1.82	6.2	8.3
	3.04	17.4	23.3
	1.82	34.1	45.7

4.2 Fuel Feed System

4.2.1 Conclusions

The test unit feed system provided an adequate seal against the positive pressure in the primary chamber provided smooth fuel flow and close control of pile height could be maintained. (See Para. 2.2 for description.) No difficulties were met with this fuel with regard to compaction of fuel in the feed tube.

Sealing of the ram tube with fuel will be improved in a full-scale unit since the distance of travel is greater.

In contrast to a side feed auger or vertical drop-in system, the potential for particulate entrainment and uneven volatiles release is minimized by under-feeding through the pile.

Low pile and high heat output conditions occasionally produced back flow of smoke through the feed tube. This may be caused by drying and devolatilization in the vertical feed pipe causing a reduction in fuel volume. The cooler environment of a full scale unit should improve this situation.

The tendency of peat to hang up in the hopper or on any surface was observed.

A cross-section of the fuel system is shown on Fig. 17.

4.2.2 Design Recommendations

The following comments have been received from K. Leppa of Ekono Inc., who was asked to provide an assessment of the Lamb metering bin:

1. Mild steel can be used as a general structural material where mechanical wear is moderate and exposure to acid peat fairly short. Bin walls should be insulated however, if there is any possibility of freezing temperatures nearby. Another possibility is to use hard plywood since it is quite insensitive to combined erosion and corrosion and resists freezing as well.

2. The combination of hard steel in drag chains and polyurethane (or Teflon) in their tracks, has been proven in operation. Again, plywood can be used in tracks.

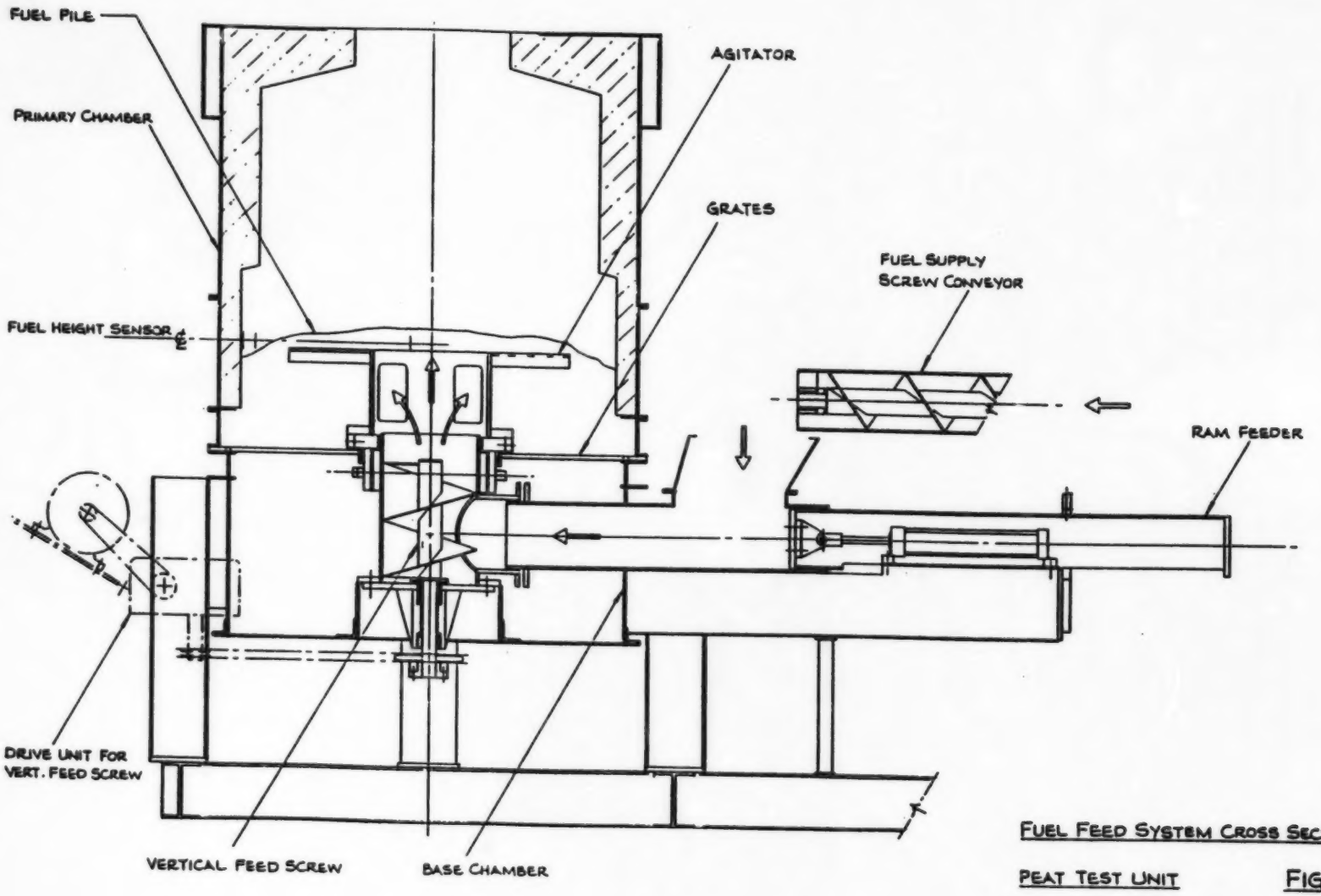
3. Based on the analysis shown and on variations likely to be encountered in year-round operation, the residence time of peat in the bin can vary between 20 and 75 minutes at full load. The turndown ratio of the variable speed drive should be able to take this variation. The critical point is the discharge chute.

4. Live-bottom bins of this height can be built with parallel walls, although diverging walls are common. One way to modify the existing design for peat would be to add a plywood lining with a slight negative inclination to the side walls; this, in case your test runs indicate there might be a problem with this particular lightweight peat. The discharge chute should be reshaped in any case.

5. The advantage of plate feeders is that their feed fluctuates less than that of drag chain feeders. In the Lamb-Cargate design however, this is not significant since the subsequent feeders will even out all fluctuations at any rate, or rather, superimpose their own cycling. The chain is no doubt cheaper.

4.3 Future Work

The tests have produced data and observations which suggest that the Lamb Gasifier/Combustor will perform well using moist milled peat fuel. It is recommended that a full-scale trial be undertaken with a commercial unit.



FUEL FEED SYSTEM CROSS SECTION

PEAT TEST UNIT FIG. 17